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14. ABSTRACT
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ABSTRACT

Naval combat platforms will increasingly operate in littoral environments where they will be exposed to a variety of anti-ship threats. To defend against these threats, a warship will use different means, including hard-kill weapons and soft-kill measures. Efficient allocation and coordination of these combat resources is a complex decision-making problem, where a huge amount of imperfect data must be dealt with, under the pressure of time. This defines the Combat Power Management (CPM) problem. Different studies have shown that experienced military operators are able to respond efficiently to multiple sequential threats; but in a situation involving massive and successive raids, their decisions tend to be sub-optimal beyond a certain number of threats. In such situations, advanced CPM decision support capabilities are required. This paper present CORALS, a CPM capability that has been developed to support the ship command team in planning optimized responses to multiple threats. One key feature of CORALS is its ability to provide different and significant decision-support capabilities ranging from optimizing deployment times for combat resources against single targets to the sophisticated coordination of combat resources for engagements involving multiple targets. The paper also discusses the Command Decision Support (CDS) lab, where CORALS is integrated.

1. INTRODUCTION

Future naval forces are expected to operate in a large variety of situations with constantly increasing complexity, where they will be exposed to various threats, including coordinated raids of advanced sea-skimming and cruise Anti-Ship Missiles (ASM). To counter these threats, a defending force, either operating alone or in consort with partners, will use different means, including hard-kill weapons, soft-kill measures, deterrence actions, and force posture and manoeuvres. Efficient allocation and coordination of these combat resources, particularly in the case of multiple-target engagements, is a very complex decision-making problem, where a huge amount of imperfect data must be dealt with, under the pressure of time. This problem is referred to as the Combat Power Management (CPM) problem.

In this context, different studies [6][16] have shown that experienced human operators are able to respond efficiently to multiple sequential threats; but in a situation involving massive raids with threats arriving simultaneously and/or in quick succession, their decisions tend to be

sub-optimal beyond a certain number of targets. In such situations, operators rely solely on (at best sub-optimal) intuition and pre-established rules. Thus, there is a need for advanced CPM decision support capabilities that would allow operators to optimize plans and execute actions against threats.

Defence Research and Development Canada (DRDC) and its partners have been conducting research that aims at demonstrating advanced decision support capabilities for the future Command and Control (C2) systems and platforms. To permit warship operators to optimally decide and engage actions against threats, a Command Decision Support Laboratory (CDS Lab) was developed under the umbrella of the Innovative Naval Combat Management and Decision Support (INCOMMANDS) Technology Demonstration Project (TDP). The overall objective of INCOMMANDS was to demonstrate advanced decision support capabilities for the future Command and Control (C2) of the Halifax Class frigates. The CDS Lab permits the conduct of experiments to measure the decision-making effectiveness resulting from the use of new Above Water Warfare (AWW) CPM, and in particular, Anti-Ship Missile Defence (ASMD) decision support capabilities.

One of the demonstrated decision support capabilities developed within the CDS Lab is the COmbat Resource ALlocation Support (CORALS) planner [3]. CORALS is a real-time planner developed to support a defending force command team during the conduct of CPM-related activities, by automatically planning actions against multiple targets, arriving from different directions. An important feature that distinguishes CORALS is its ability to compute defense plans against multiple simultaneous targets. The output of CORALS is a plan that maximizes the overall Probability of Raid Annihilation (PRA), which is a combination of the probabilities of the successful engagement of the different individual targets.

This paper presents CORALS and the Command Decision Support (CDS) lab, where CORALS is integrated. The remainder of this paper is organized as follows. Section 2 presents a discussion on the Combat Power Management (CPM) problem in the context of naval Command and Control (C2). Section 3 presents the CDS Lab, discusses its components and the integration of CORALS into it. Section 4 presents the components and features of CORALS and discusses state-of-the-art planners related to it. Finally, Section 5 concludes with a discussion of future works.

2. COMBAT POWER MANAGEMENT

This section presents a broad discussion on the Combat Power Management (CPM) problem in the context of naval C2. The latter designates the exercise of authority (i.e., command) and direction (i.e., control) by commanders over the naval forces under their supervision to accomplish given missions. The ultimate goal of C2 is to accomplish mission objectives, which

may be, for instance, to defend a given area, escort civilian platforms, or provide fire support to friendly forces.

2.1. CPM AND THE NAVAL C2 PROCESS

Naval C2 conveys very complex decision-making problems due to the heterogeneity and the inter-relationships of the environment, systems and resources involved. This is, in general, the case when simultaneous engagements involving heterogeneous sensors and/or weapons systems take place, and human operators have to make a large part of the decisions. Figure 1 shows a high-level description of the naval C2 process. The process follows a generally accepted decomposition that must be concurrently executed within some reasonable delays to ensure mission success. These include: picture compilation, threat evaluation, engageability assessment, and combat power management.

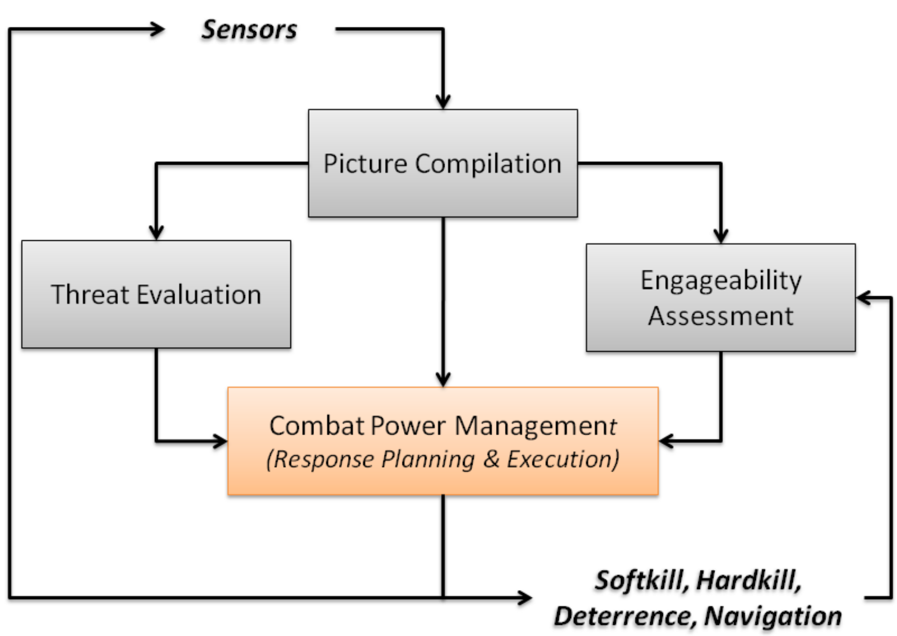

Figure 1: Overview of the C2 process

The picture compilation process includes: object detection, object localization, and object recognition and identification. Object detection, which is very dependent on the performance of the sensors, may be based on data from a single sensor or a combination of several sensors. Object localization, also referred to as tracking, uses the sensor data to estimate the current kinematical properties of the object, and predict its future positions. Object Recognition and Identification (R&I) assesses respectively the identity (based on NATO criteria) and the class of objects.

The Threat Evaluation (TE) process determines the level of threat of non-friendly objects within a certain Volume Of Interest (VOI). Typical criteria for evaluating the level of threat for a given object are the intent, the capability and the opportunity the object may have to inflict damage to own-force. This results in a list of objects ranked by their threat levels[1].

The engageability assessment process concerns the evaluation of feasible options of own force's engagement against non-friendly objects within the VOI. This process is intended to help the process of CPM by eliminating candidate solutions that violate one or more hard constraints. Such solutions will therefore not be feasible. Several aspects can be taken into consideration during this process, such as Rules Of Engagement (ROEs), weapon-target pairing appropriateness, blind zones, and ammunition availability. Engageability assessment is a mirror to threat evaluation since the former is concerned by the own-force capability (blue perspective) analysis, whereas the latter deals with hostile capability (red perspective) analysis.

The CPM process makes decisions on how to deal with the identified threats, which at this point are considered as targets. In its general form, the CPM problem goes beyond the classical Weapon Assignment (WA) problem [3]. In its pure theoretical definition, WA is only concerned with "weapon-target" pairing, abstracting away scheduling and coordination aspects.

2.2. CPM Characterization

The CPM problem, which is very important in many military planning applications, consists in: (i) generating a plan to defeat threats; (ii) executing the plan by engaging the threats; (iii) monitoring the execution of the plan to detect, assess and handle contingencies; and (iv) assessing the outcome of executed actions (i.e., assessing the damage inflicted to engaged threats to determine to what extent the engagement objectives were attained). In this context, an action is defined as the application of some combat resource in a single step (e.g., firing a missile against a threat; or launching a decoy). In general, combat resources include hardkill weapons (e.g., missiles and guns), softkill weapons (e.g., jammers and chaff), deterrence measures, and ship manoeuvres.

Planning actions against targets is a complex problem for warship commanders, particularly in situations involving simultaneous engagements. The complexity arises from a combination of factors [1][2][13], including the following:

- Some of the key parameters, such as target identity and localization, required for determining the use of combat resources are subject to uncertainty.

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[1] Depending on approaches, threats may be further classified into threat level classes (*e.g.*, Low, Medium, High), each class containing a list of ranked threats.

- Combat resources have different probabilities of successfully defeating threats according to circumstances. Moreover, combinations of combat resources can have different probabilities of effectiveness against targets. Even a single target may have to be engaged by coordinated combat resources to maximize the probability of defeating it.

- There are often different kinds of constraints on the use of combat resources. In particular, weapon types are effective within specific ranges and soft-kill decoys remain in the air for specific time windows.

- Other factors, such as deadlines for engaging targets may contribute to the complexity of the problem.

Therefore the CPM problem is not just about deciding which combat resources should engage which target. It is also about deciding when is the best time for actions to be executed, and how those actions should be coordinated with past, current and future actions, to minimize negative interferences and maximize positive interferences.

A recent study focused on the characterization of the CPM problem, a review of technological solutions applicable to the design of CPM planner, and recommendations for the most appropriate technological solutions [2]. The problem characterization showed that the CPM problem is an ongoing sequential decision-making problem, requiring the ship's commanders to respond to continually changing situations. Responses must be aimed at maximizing, for the defending ship, the overall Probability of Raid Annihilation (PRA). Four key decision-making sub-problems have been identified:

- Planning, scheduling, and coordinating the use of combat resources to defeat threats.

- Responding to unanticipated events and situations, such as new threats, and changes in threat status.

- Assessing the outcome of actions taken against targets.

- Detecting and recovering from failures.

2.3. Approaches to the CPM Problem

A survey of the literature by the mentioned study showed that none of the existing approaches comprehensively addresses all aspects of the CPM, since they all make different simplifying assumptions. Different approaches have different virtues and limitations, depending on the assumptions they make to simplify the problem and the algorithms they use to solve it. The vast majority of approaches consider formulations of the Weapons Assignment problem

that consists only in pairing weapons with targets, abstracting away other aspects of the problem [2]. In particular, many Weapons Assignment formulations do not consider scheduling aspects (i.e., the Weapons Assignment does not involve assigning actions over time periods); others do not explicitly handle interferences among actions (i.e., do not check nor resolve conflicts among actions). Furthermore, most approaches do not consider time constraints or actions undertaken against targets in a sequence over a given time horizon.

There are generally two main formulations of the CPM problem in the literature: *episodic* (also called static in some references) and *sequential* (also referred to as dynamic by some authors). The episodic formulation consists in finding, in a single step, weapons/targets pairings that maximize the expected survival value of the defending force, while the sequential formulation considers the dynamic and time-dependent nature of the decision-making problem. Even under the ‘‘simplifying’’ episodic assumption, the problem is known to be NP-complete [12].

A survey of early Operational Research approaches, back in the 1970s, is given in [13]. Most of these approaches were based on linear integer programming, with few considering heuristic search. More recent approaches still use the same basic techniques, but rely on enhanced implementations [1][5][10]. The fact that the Weapons Assignment problem has been, to date, mostly studied in the Operational Research literature is not surprising, since dealing with resources and durative actions is very common in that field. There exist efficient scheduling algorithms that use heuristics to maximize various types of objective functions other than makespan [7]. However, Operational Research approaches have been essentially limited to the episodic formulation of the (Weapons) Assignment problem.

The very few exceptions that considered the sequential aspect of the CPM problems from a formal perspective include [11]. However, the authors did not address durative actions. Other approaches have proposed to solve the problem as a Markov Decision Process [4][15], but they do not handle durative actions either.

An in-depth analysis of the CPM problem suggested that a key element for solving it efficiently would be to reason explicitly about actions - that is, about the preconditions and effects of actions and about how actions interfere with each other. Reasoning about actions is more a feature of Artificial Intelligence (AI) planning approaches than Operational Research approaches. There exist few planners in the AI planning literature that can handle concurrent durative actions with probabilistic effects, such as those characterizing the CPM domain. Three of the most renowned are Tempastic [17], DUR [14], and FPG [8]. Tempastic follows an event-based modeling that does not naturally fit the CPM domain. DUR is limited to a small number of actions. FPG presents a planner which, among the three, best meets the requirements of the

CPM domain. However it does not permit probabilistic effects that depend on time, which is a crucial requirement in the CPM domain.

3. COMMAND DECISION SUPPORT LAB

The CDS Lab, the architecture of which is illustrated in Figure 2, integrates several Commercial Off The Shelf (COTS) applications and developed custom applications.

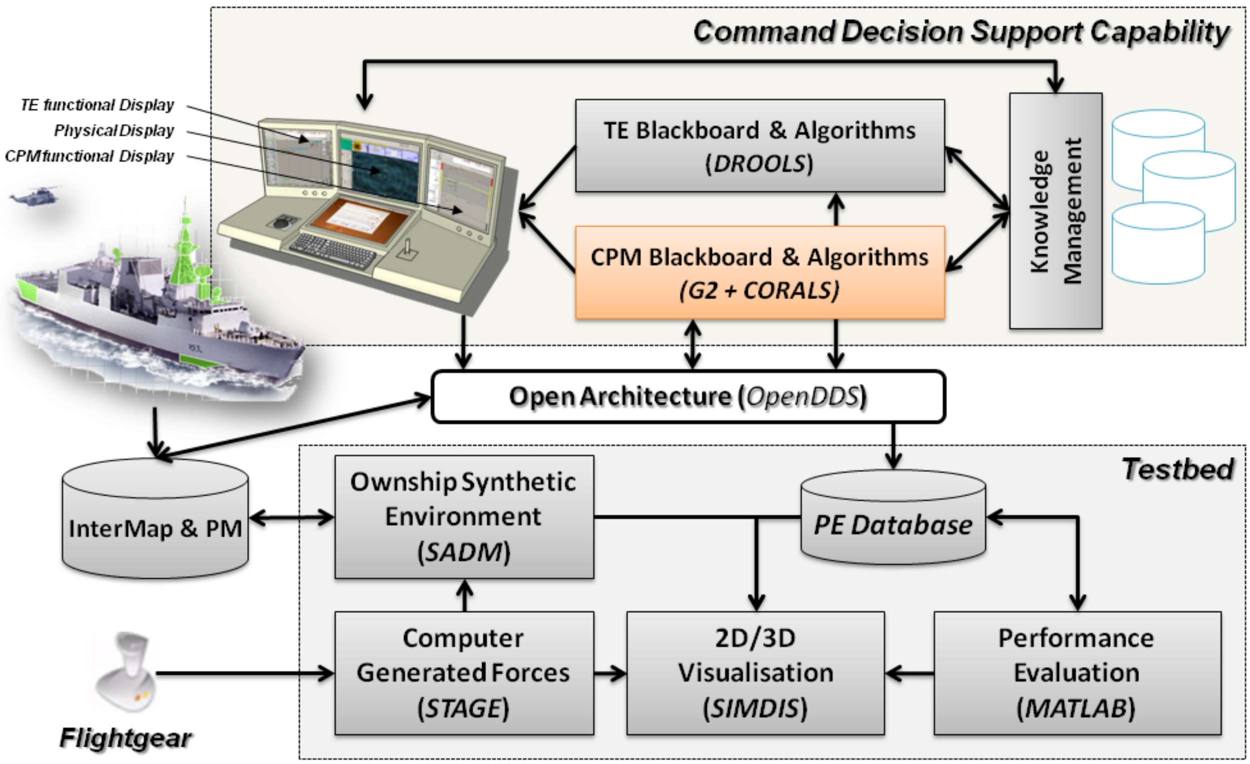

Figure 2: Command Decision Support Lab

The overall architecture of the CDS Lab is based around the OpenSplice Data Distribution System (DDS). This DDS uses a publish/subscribe paradigm where different software components that comprise the system are very loosely coupled. Such an architecture allows for easy replacement of components (*e.g.*, a component that performs a given item of functionality can be easily replaced by one that implements the same functionality, but in a completely different way), and for the easy addition of new components. The new or upgraded components simply have to conform to the defined data model - the manner in which they process the data is of no concern to the other system components.

The main components of the CDS Lab are described in the following sections.

3.1. Computer Generated Forces

The purpose of the Computer Generated Forces (CGF) capability is to simulate the kinematical and non-kinematical behaviours of a set of ground truth objects representing aircrafts, missiles, and ships in the tactical combat environment of ownship. In the testbed, Preagis STAGE is used mainly to provide a means by which to define scenarios.

3.2. Ownship Synthetic Environment

The purpose of the Ownship Synthetic Environment component is to provide a synthetic representation of the ship on which the operators serve and to simulate the behaviour of a subset of the entities present in a simulated engagement. The Ship Air Defence Model (SADM), developed by BAE Systems, provides models that support Air-to-Surface engagement, Surface-to-Air engagement, and naval gunfire support engagement.

3.3. Air Entity Controller

The Air Entity Controller component provides the testbed with the ability to have a synthetic (ground truth) entity piloted by a human. The CDS Lab testbed uses the FlightGear product to allow the integration of a flight simulator into SADM in order to model tactics against realistic attack profiles. This capability allows human pilots to control attack profiles against ships and enables the evaluation of weapons, sensors and system performance against these threat profiles.

3.4. 3D Visualization Tool

SIMDIS, a Government Off The Shelf (GOTS) product developed by the Naval Research Lab, is used to provide a 2D and 3D rendition of the synthetic environment to assist in the control and management of the environment and the stimuli presented to the operators. SIMDIS provides a 3D visual picture compilation of SADM's ground truth entities and their radar detected system tracks.

3.5. Intermap Database

The testbed has the capability to process a ship's data, both recorded and live, through the integration of the Intermap Database application. It consists of an Oracle database along with a software application (Intermap Database Data Logger) that provides data logging, parsing, and extraction functionalities.

3.6. INCOMMANDS Module Input Output

The INCOMMANDS Module Input Output (IMIO) application is used to mediate the interaction of STAGE, SADM, and the Stimulation Control Gateway with the Intermap database.

The IMIO application extracts data from the Intermap database to provide to STAGE, SADM, and the Stimulation Control Gateway, and receives data from these applications, which is then logged into the Intermap database.

3.7. Data Recording and Storage Capability

Data collected from the CDS Lab is placed in an ORACLE Enterprise Manager database for short and long-term storage. The ORACLE Data Recording and Storage capability provides the means to access on-line and off-line storage media.

Performance Evaluation Database Logger provides a custom developed application that simply subscribes to all topics published on OpenSplice by other components of the CDS Lab. It reads all OpenSplice topic instances and stores them in the Performance Evaluation Database to facilitate both online and offline data analysis.

3.8. Performance Evaluation Capability

The purpose of the Performance Evaluation Capability is to collect and analyze the raw measurements of a given experiment, perform whatever analysis is called for in the experimentation plan, and prepare the necessary reports to conclude the experimentation activity. Performance evaluation can be carried out during the experiment (on-line analysis) or once it is over (off-line analysis).

3.9. Functional Operator Machine Interface

Based on the decision support and information requirements, new and advanced Operator-Machine Interfaces (OMIs) have been designed and developed. The resulting Threat Evaluation (TE) and Combat Power Management (CPM) displays provide a functional representation of information offering micro and macro support, explanation facilities and function-based alarm decision support. The design rationale is that decision making is facilitated when a higher level of data abstraction is presented from a functional versus a physical perspective.

3.10. Physical display

The physical display provides a two dimensional range-based perspective of the world where entities, including the ownship, are displayed according to their physical location and course. The physical display used in the CDS Lab was developed based on the SIMDIS component by developing a plug-in library that adds a display layer on top of the standard SIMDIS display.

3.11. Automation algorithms

Algorithms that provide threat categorization and ranking have been developed and tested on both simulated and real data.

CPM automation algorithms were also developed to provide a coordinated and conflict free plan for multi-target engagements in Anti-Ship Missile Defence (ASMD) operations. The CDS uses two ASMD planning capabilities, i.e., G2 and CORALS.

3.12. G2 ASMD Tool

G2 is an ASMD aid tool that takes as input a single target (including its characteristics: type, range, speed and Closet Point of Approach) as well as wind conditions, and returns a plan for hard-kill and soft-kill actions against the target. The hard-kill combat resources handled by G2 are Evolved Sea Sparrow Missile (ESSM), Intermediate Range Gun (IRG) and Close-In Weapon System (CIWS). The soft-kill combat resources are Chaff and jammer.

Within the CDS Lab, G2 was subsumed by CORALS, discussed in detail in the next sections.

4. CORALS PLANNER

CORALS is an automated planning system that supports ship operators in optimized planning and executing engagement actions. Although the concepts and solutions explored by CORALS remain applicable to Anti-Subsurface (ASW) Warfare, the current implementation is limited to Above-Water Warfare (AWW), and more specifically to ASMD. One key feature of CORALS is its ability to provide different and significant decision-support capabilities ranging from optimizing deployment times for combat power resources against single targets to the sophisticated coordination of combat power resources for engagements involving multiple targets. Coordination is performed by eliminating negative interference among actions, and taking advantage of positive interactions, through a plan-merging process that combines multiple single-target plans into a conflict-free multi-target defence plan.

When it comes to applications of planning, there is a large spectrum of possibilities between domain-specific planners and general-purpose planners. CORALS planner lies somewhere in-between, as it relies on domain-independent heuristics and does not make use of any domain knowledge (other than action specifications). CORALS has an algorithm that quickly generates local plans, which may contain conflicts, and then checks and resolves those conflicts efficiently.

In order to understand how CORALS works, the remainder of this section provides a detailed insight into the underlying architecture, concepts, and algorithms.

4.1. Architecture

Figure 3 describes the CORALS planner architecture. CORALS takes as input a list of targets (together with corresponding features, including type, range, and speed), ship parameters (including the ship's position, heading, etc), combat resources information (including

corresponding features, constraints, and probability of success), and wind parameters (required for the chaff deployment). It returns an optimal plan against all the input targets.

For each of the targets, CORALS calls a local planner to obtain a local plan, and then a plan optimizer to locally improve the plans. The optimal local plans are then merged into an optimal multi-target plan by using the plan merger. The following sections provide details on the design of each of the three main building blocks: local planner, local plan optimizer and plan merger.

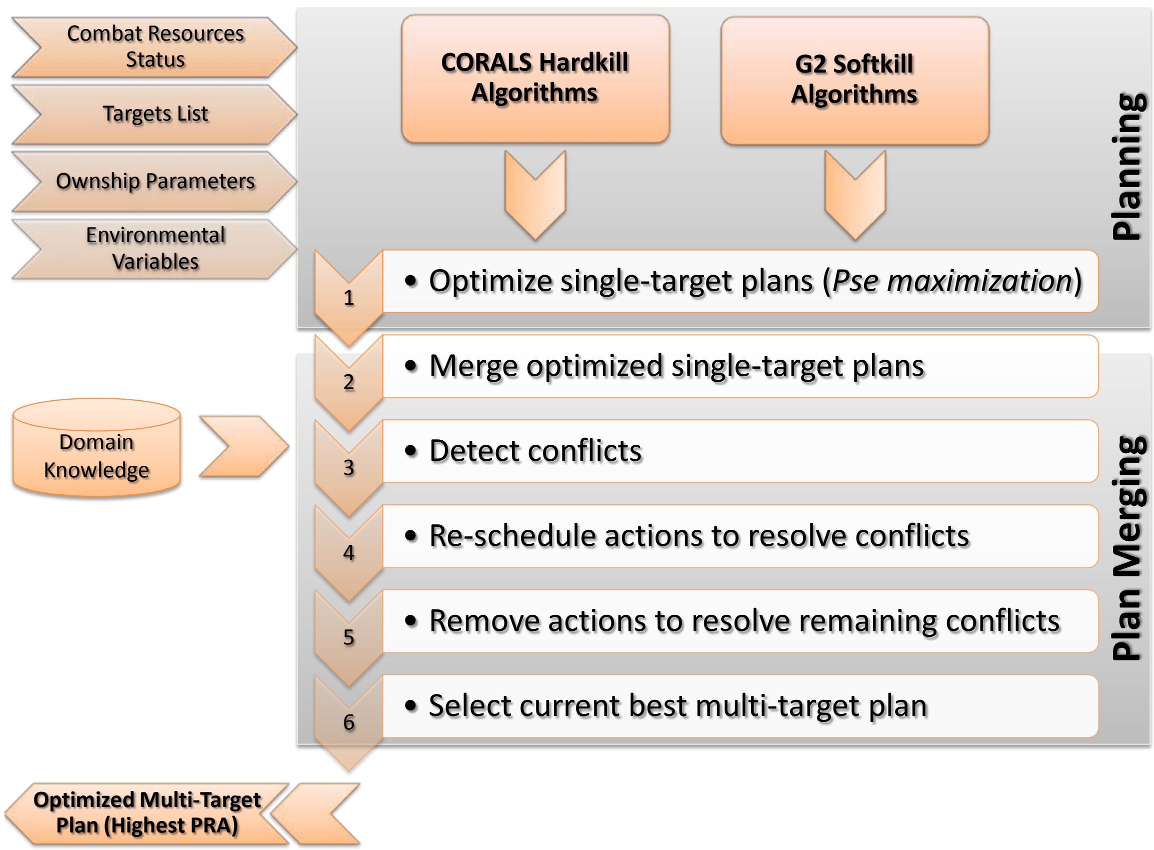

Figure 3: CORALS Internal Architecture

4.2. Actions

An important concept in CORALS is that of action. An action in CORALS is the application of one or more combat resources in a single procedure against one or more targets during a given time period. For instance, launching a missile or a salvo of gun rounds against a target during some time period is an action. Launching chaff against one or more targets during a given time period is another action. The time period for an action is specified by its start and end times.

Besides the time periods, an action is associated with different types of information which are used by CORALS planner to determine how actions can be selected and combined into a defense plan for a given list of targets. Two types of knowledge are implemented:

- Action enabling constraints relating to the availability of combat power resources used by the action and the appropriateness of their application in a given context ; and
- Probability of Successful Engagement (P_{SE}) specifying the expected effectiveness of an action on a target.

Information about the appropriate context of application of a combat resource includes targets it can be used against, the range envelope (i.e., distances beyond which it is ineffective against targets) and, for some combat resource types, certain parameters relative to their use, such as the number of rounds, the reload time (e.g., the time required to reload a gun), the turning speed (i.e., the speed at which a weapon turns when it is being repositioned against a new target coming in on a different bearing), bearing limits (i.e., blind zones within which a combat resource is ineffective).

Combat resources are also associated with Probability of Successful Engagement (P_{SE}) functions. These P_{SE} functions are inherited by the actions using those combat resources.

CORALS can be customized to handle actions for different domains of application by specifying the types of actions that are applicable in those domains. Given a particular domain of application (e.g., ASMD in our case), the different types of actions applicable are specified as action templates. Each action template describes the parameters used by the action (including the target and the combat resource), the duration of the action, the constraints, and the effects of that action on the target and on combat resources (including possible interferences). Such action templates are seen herein as action types, but they are usually called *planning operators* in the AI planning literature [9]. The specification of action types defines a particular *planning domain*.

The ASMD domain implemented in CORALS contains five action types corresponding to five different types of combat resources on the Halifax Class Frigate: Evolved Sea Sparrow Missile (ESSM), Intermediate Range Gun (IRG), Close-In Weapon System (CIWS), jammer, and chaff. The first three types of actions are *hardkill actions* since they are intended to destroy the target on impact. The last two types of actions are *softkill actions* given that they are intended to distract or to deviate the target from the defended asset. Each action type is implemented as a template with several attributes. CORALS also handles a Separate Tracking and Illuminating Radar (STIR) as a combat resource supporting the application of ESSMs and IRGs.

4.3. Plans

A *response plan* (or simply a *plan*) is a set of *actions* to be applied against a target or a group of targets. A plan for a single target is also called a *local plan*, whereas a plan for several targets is called a *multi-target plan*. From a syntactic point of view, a multi-target plan is a union of

actions from a set of coordinated local plans. Figure 4 shows an example of a multi-target engagement plan generated by CORALS, where two targets are engaged (two local plans separated by the grey line) simultaneously, with different combat resources, distinguished by different colour codes. These plans are presented to the human operators through the CPM functional display (Figure 2).

Henceforth, the term *plan* will be used to refer to a multi-target plan, of which the local plan is a particular case. The qualifier "local" will be added whenever needed to highlight a single-target context. The most trivial plan is the empty set (plan), which consists in doing nothing. The next simplest plan is a singleton, i.e., a plan containing only one action.

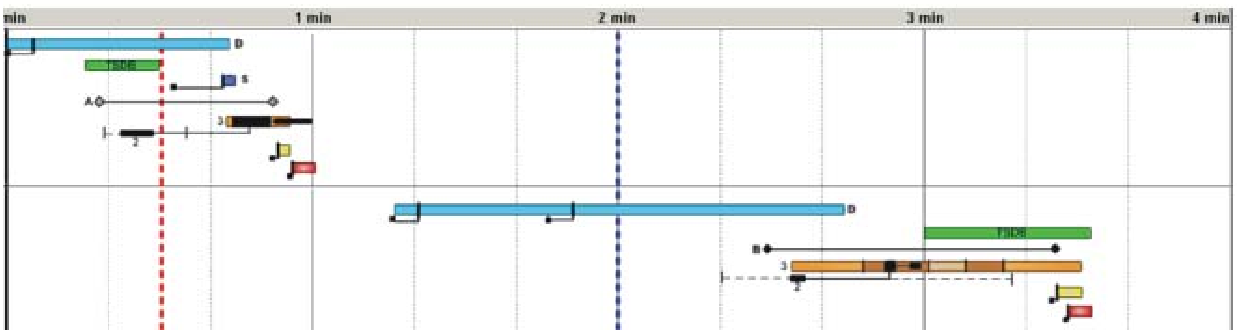

Figure 4: Example of Engagement Plan Generated by CORALS

4.4. Decision criteria

Given a list of targets and a planning domain (i.e., a specification of all possible actions), there can be many different plans. In order to generate an optimal plan, one thus needs decision criteria specifying the minimal conditions a useful plan must satisfy and the objective function the best plan should optimize.

CORALS assumes that plans containing conflicts are not executable. Here, by conflict it is meant the violation of a given constraint by a subset of actions in the plan. The subset of actions causing a conflict is referred to as conflicting actions. A constraint violation of one action (i.e., the subset of conflicting actions is a singleton) is also a conflict. An example is an action using a combat resource in its blind zone. This is language abuse allowed for the sake of simplicity; otherwise an action cannot be in conflict with itself. With this terminology, a conflict becomes just any constraint violation, whether involving one or more actions. Thus the minimal requirement that a plan must satisfy is the absence of conflicts among its actions.

The optimality criterion is conveyed by an objective function, which is referred to as the *plan-quality metric function* or plan-quality function. This is a function that takes a plan as input and returns a real number expressing the quality of the plan on some scale. The optimal plan is a conflict-free plan having the highest plan quality.

There can be different formulations of the notion of *plan quality* depending on choices and preferences of the domain expert (e.g., it may be set by the ship's command team during the mission planning phase). Accordingly, in CORALS, the plan-quality function is an option selected by the human operator. There are currently two implemented options the operator can choose from:

- Own-force survival probability: This measures the probability of own-force surviving an attack by threats.
- Expected threat survival level: Each target is attributed a real value based on its threat level. This way, the expected threat survival level for a given target is the threat level multiplied by the probability that all plan actions engaged against it fail. The expected threat survival level for the entire plan is the sum of expected threat survival levels for individual targets.

One may also want to involve the cost of combat resources in the definition of a plan quality. One may further want to take into account the ship's survival value (i.e., taking into consideration a partial damage) instead of just considering the ship's survival probability. Such plan quality functions are not presently supported by CORALS but remain potential future extensions.

Depending on the planning problem complexity, the time required for CORALS to succeed in computing an optimal solution may be longer than the time available for responding to threats. Knowing that CORALS proceeds by generating a sequence of conflict-free plans that are increasingly closer to the optimal, the operator can specify a maximum planning time, on the basis of the available reaction time and the characteristics of own combat resources. If this time is reached, the best plan computed so far is returned, albeit it may not be optimal. That way, the maximum planning time is somewhat part of the decision criteria.

4.5. Algorithms

The input to CORALS is a list of targets and its output is a plan against those targets. For each target, a local plan is computed by a *local planner* and optimized by a *local plan optimizer*. A *plan merger* then generates a multi-target plan starting from a union of the optimized local plans, and iteratively detecting and resolving conflicts among actions in those plans, i.e., repairing the union of the local plans.

4.5.1. Local planner

CORALS allows the use of different local planners that may better fit particular domains. The default local planner is an ASMD planner that generates a local plan against a target based on provided P_{SE} tables.

4.5.2. Local-plan optimizer

The local plan optimizer takes as input a local plan, the target information, and the P_{SE} functions for the different combat resources. It returns an optimal local plan obtained by changing the start time of each action to make the target interception occur at the highest P_{SE} value.

4.5.3. Plan merger

The plan merger is the most elaborate algorithm in CORALS. It takes as input a set of optimized local plans and returns a multi-target conflict-free plan by merging local plans and repairing the resulting plan. The returned plan is optimal if enough computation time is available. The plan merger process consists mainly in modifying the plan resulting from the merger as to remove conflicts. To do so, the algorithm generates a search graph representing the space of all possible plan modifications, such that each node in the graph corresponds to a plan, and transition from plan P_1 to plan P_2 represents a transformation of P_1 into a new plan P_2; that is, a transformation that removes a conflict from the plan P_1. Thus a path in the graph is a sequence of plan modifications. The root plan is the multi-target plan which is a union of optimal local plans.

4.6. Integration of CORALS into CDS Lab

Figure 5 shows the architecture for the integration of CORALS into the CDS Lab. The existing communication between CORALS and G2 (through TCP/IP sockets) has been extended to include a CORBA connection to allow communication between CORALS and the CDS Lab. The TCP/IP and the CORBA connections together constitute the CORALS Service package.

All the communications between the CDS Lab and CORALS pass through the CORBA connector of CORALS Service. There are two kinds of information exchanged through the CORALS Service:

- A priori knowledge, which is static information that does not change over time, such as the P_{SE} tables. This information is stored in a dedicated database within the CDS Lab. When needed, the information is delivered through the APRIORI Service. The latter enables CORALS to retrieve a priori knowledge that is relevant for its planning processes.

- Context information (also referred to as dynamic information) is information relating to the targets (speed, bearing, type, etc), the ownship (speed, bearing, available combat resources, etc), and the surrounding environment (wind speed, wind direction, etc), as well as plans and control information (e.g., for notification of the availability of new data and for synchronization). The CDS Lab is responsible for monitoring the information about the targets, the ownship and the surrounding environment, and communicating it to

CORALS. CORALS is responsible for providing a multi-target plan that takes into account the current tactical situation, combat resources status, and the plan execution details. Control information travels in both directions between CORALS and the CDS Lab. The exchange of this information, inside the CORALS Service, involves monitoring and notification processes.

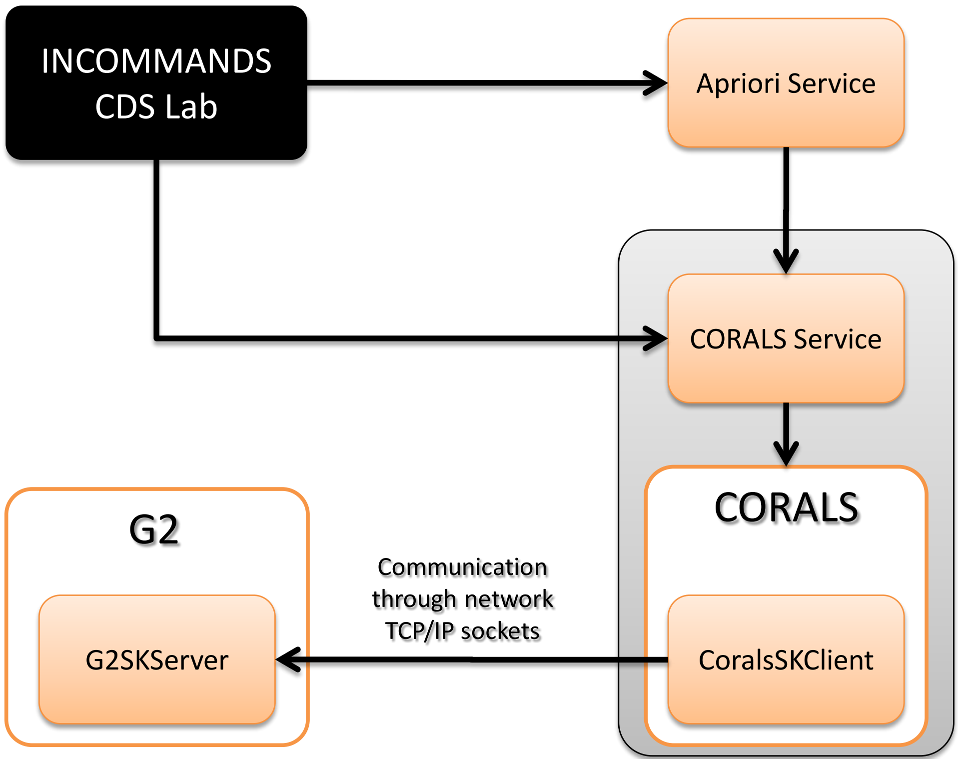

Figure 5: Integration of CORALS in CDS Lab

All communications between CORALS and G2 pass through the TCP/IP connection of the CORALS Service.

4.7. Performance of CORALS

The comparison of features and options of CORALS and those of existing planning systems led us to conclude that no other existing system suits the CPM domain like CORALS. In particular, the only system that came closer to fitting the CPM domain (namely, FPG planning system [8]) does not support actions with effects characterized by a time-dependent probability. Yet, this is an important feature of the CPM domain since the kill probability is generally function of range, hence of time as well. This comparison provided elements supporting the originality and significance of CORALS. Preliminary results of the analysis were published in [3].

Although the motivation behind the development of CORALS has been a requirement for naval warfare operations, its generic implementation makes it suitable for any domain that deals with planning with resources under constraints. CORALS is an activity-oriented planner, which provides planning solutions given a set of related activities and an objective function conveying the goal to be achieved by them. When applied to the CPM domain, activities correspond to neutralizing targets and the goal to the maximization of the probability of raid annihilation.

5. DISCUSSION

This paper presented CORALS, an automated planning system that supports ship operators in optimally planning and executing engagement actions. The current implementation of CORALS is along a single-platform perspective. Work is in progress to expand the system to force-level operations, so that a distributed version of CORALS (Force CORALS) will produce a force-wide conflict-free and optimized response plan, taking into account the geographical dispersion of both the combat resources and the protected assets. We are also investigating a mixed-initiative planning approach, in which the planning elements are contributed both by the automation algorithms and the human operator. In such a setting, the operator may suggest alternative options to CORALS or enforce planning steps and constraints.

Although the CORALS version presented here has proved to be efficient during experimentation, there is still room for improvement. One improvement possibility would be to introduce a technique of planning by decomposition. The idea is to group targets into classes based upon a measure of urgency, such as the target time to reference point. This way, local plans would be calculated and merged into incremental phases, each phase dealing with a level of immediacy.

The types of combat resources could also be extended to include ship navigation, deterrence, and actions that can produce an effect on several targets simultaneously; that is plan for, and benefit from, a synergetic effect.

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